Multichannel calculation of D_s^* vector states and the $D_{sJ}^+(2632)$ resonance.

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Abstract

We study bound states below threshold and resonances above threshold in the D^0K^+ and $D_s^+\eta$ systems, using a many-coupled-channel model for non-exotic meson-meson scattering applied to states with the quantum numbers of $c\bar{s}$ quark-antiquark vector mesons. We fit the ground state at 2.112 GeV, whence the lowest resonances in D^0K^+ come out at 2.61, 2.72, 3.03, and 3.08 GeV. The resonance at 2.61 GeV acquires a width of about 8 MeV, while its partial P-wave cross section is up to six times larger in $D_s\eta$ than in D^0K^+, provided a mechanism accounting for Okubo-Zweig-Iizuka–forbidden decays is included. The latter finding is in agreement with the observations of the SELEX collaboration [1] with respect to the recently reported $D_{sJ}^+(2632)$ resonance. Therefore, we conclude that the $D_{sJ}^+(2632)$ is probably the first recurrence of the $D_s^*(2112)$ meson.

1 Introduction

The very fortunate discovery [1] of a new resonance in both the D^0K^+ and $D_s^+\eta$ channels has been awaited for over two decades [2]. Excitations of $J^P = 1^-$ $c\bar{s}$ states have been foreseen in the past, but with higher masses. For instance, in Ref. [3] two states were forecast at 2.73 and 2.90 GeV, one for each of the possible angular configurations S and D, whereas in Ref. [4] these states were predicted at 2.773 and 2.813 GeV. Nowadays, a mass of 2.632 GeV is of no surprise. Just consider the mass differences between the ground states and first radial excitations of other $J^P = 1^-$ mesons, which vary from 0.52 GeV for K^* to 0.59 GeV for $c\bar{c}$. The $D_{sJ}^+(2632)$ resonance, being 0.52 GeV heavier than the D_s^* ground state, could thus perfectly well turn out be the first radial excitation of the $D_s^*(2112)$ meson. However, the branching ratio of its two decay modes, i.e., D^0K^+ to $D_s^+\eta$, with the latter one dominating by a factor of six, seems to be problematic [1, 5]. Also its decay width (smaller than 17 MeV [1]) is smaller than expected for a $c\bar{s}$ resonance with sufficient phase space in a two-meson channel observing the Okubo-Zweig-Iizuka (OZI) [6] rule.

This small decay width, and the puzzling branching ratio to D^0K^+ and $D_s^+\eta$, are explained by Maiani *et al.* [7] assuming a dominantly $[cd]\left[\bar{d}\bar{s}\right]$ four-quark configuration, whereas Liu *et al.* [8] argue that the $D_{sJ}^+(2632)$ resonance may be a member of a flavor 15-plet, which is a mixture of $[cu]\,[\bar{u}\bar{s}]$, $[cd]\left[\bar{d}\bar{s}\right]$, and $[cs]\,[\bar{s}\bar{s}]$. Other tetraquark proposals can be found in Refs. [9] and [10], namely $[c\bar{s}]\left[u\bar{u}+d\bar{d}\right]$ and $[cd]\left[\bar{d}\bar{s}\right]$, respectively. A radial excitation of the D_s^* is suggested in Refs. [5, 11], among other possibilities.

Here, we shall show that the observed properties are compatible with the predictions of a multichannel quark-meson model, designed to describe mesonic resonances in terms of systems of coupled $q\bar{q}$ and two-meson states [12]. However, the study of non-ground-state D_s^* vector mesons requires a more elaborate approach than the one previously applied by us to scalar mesons [13], as we shall explain in the following.

In the first place, $J^P = 1^-$ systems consisting of a charm quark and a strange antiquark may appear in two different orbital excitations, namely $\ell = 0$ and $\ell = 2$. This implies that instead of one $c\bar{s}$ channel, as in the case of the $D_{s0}^*(2317)$ resonance [14], we must now consider two such channels.

Secondly, higher radial and angular excitations of $c\bar{s}$ can decay into a variety of different OZI-allowed two-meson channels, while the influence of nearby closed two-meson channels must be taken into account, too. In Table 1, we summarize the twenty-eight mesonic decay channels of the $c\bar{s}$ system that we consider of importance in the energy region of interest.

Thirdly, the phenomenological Resonance-Spectrum-Expansion (RSE) formalism employed in Refs. [13, 14] is not practicable in the present case, exactly because of the proliferation of relevant two-meson channels involved. In the RSE method, one term in the expansion accounts for one radial or angular $q\bar{q}$ channel coupled to one meson-meson channel. Now, each term comes with a different parameter for each combination of one of the $c\bar{s}$ channels and one of the two-meson channels. Thus imagining four terms in the expansion, then with two channels in the $c\bar{s}$ sector and twenty-eight channels in the two-meson sector we would end up with many

parameters: clearly enough to fit anything, but not very useful for predictions.

Nonetheless, with a definite choice for the confinement potential, these ambiguities are readily removed. Here, we opt for a harmonic oscillator, which has the additional advantage that the relative decay couplings, given in Table 1, can be determined through the formalism developed in Ref. [15].

Since, moreover, we consider only one flavor state with reasonably heavy decay products, it is justified to work in the spherical-delta-shell approximation for the $^3P_0$ communication between the $c\bar{s}$ and two-meson sectors. Thus, we shall employ here the model developed in Ref. [16] for $c\bar{c}$ and $b\bar{b}$ states, and generalized to other flavors in Ref. [17]. The relative couplings are determined with the formalism from Ref. [15], where it is assumed that each decay product takes over one of the original constituent quarks. Other processes are here classified as OZI forbidden.

channel	threshold		relative couplings	
	GeV	(L,S)	to $\ell=0$	to $\ell=2$
D^0 - K^+	2.358	(1,0)	1/72	1/216
D^+ - K^0	2.367	(1,0)	1/72	1/216
D^{*0} - K^+	2.500	(1,1)	1/36	1/432
D^{*+} - K^0	2.508	(1,1)	1/36	1/432
D_s^+ - η	2.516	(1,0)	1/108	1/288
D_s^{*+} - η	2.660	(1,1)	1/54	1/648
D^0 - K^{*+}	2.756	(1,1)	1/36	1/432
D^+ - K^{*0}	2.766	(1,1)	1/36	1/432
$K_0^*(800)$ - D^*	2.838	(0,1)	1/24	1/216
		(2,1)		1/216
D^{*0} - K^{*+}	2.898	(1,0)	1/216	1/648
		(1,2)	5/54	1/3240
		(3,2)		7/120
D^{*+} - K^{*0}	2.906	(1,0)	1/216	1/648
		(1,2)	5/54	1/3240
		(3,2)		7/120
D_s^+ - η'	2.926	(1,0)	1/216	1/648
D_s - ϕ	2.988	(1,1)	1/36	1/432
D_s^{*+} - η'	3.070	(1,1)	1/108	1/1296
$f_0(980)$ - D_s^*	3.092	(0,1)	1/48	1/432
		(2,1)		1/432
D_s^* - ϕ	3.132	(1,0)	1/216	1/648
		(1,2)	5/54	1/3240
		(3,2)		7/120
$D_0^*(2308)$ - K^*	3.201	(0,1)	1/24	1/216
		(2,1)		1/216
$D_{s0}^*(2317)$ - ϕ	3.337	(0,1)	1/48	1/432
		(2,1)		1/432

Table 1: The pseudoscalar-pseudoscalar, pseudoscalar-vector, vector-vector, and scalar-vector real and virtual OZI-allowed two-meson channels, for $L = 0, 1, 2, 3$, considered throughout this work, their thresholds, and relative couplings squared to each of the two $c\bar{s}$ channels. For η and η' we assume flavor octet and singlet, respectively. Experimental masses are taken from Ref. [18], except for the $D_0^*(2308)$ [19] (see also Ref. [14]), and the $K_0^*(800)$ (or κ) [18]. For the latter resonance, we choose the peak mass of 830 MeV from Ref. [13].

2 Inelastic meson-meson scattering

The 28×28 scattering matrix S, as a function of the total center-of-mass energy $\sqrt{s}$, has the familiar form

$$S\left(\sqrt{s}\right) \;=\; k^{1/2}\;\left[1-iK\right]^{-1}\;\left[1+iK\right]\;k^{-1/2}\quad , \tag{1}$$

where k and L can be represented by diagonal matrices containing the linear and angular momenta of each of the two-meson channels, respectively. The elements of the matrix k are determined through the kinematically relativistic expression

$$4sk_i^2\left(\sqrt{s}\right)=\left[s-\left(m_{1i}+m_{2i}\right)^2\right]\left[s-\left(m_{1i}-m_{2i}\right)^2\right], \tag{2}$$

where m_{1i} and m_{2i} stand for the meson masses involved in the i-th two-meson channel. The 28×28 inverse cotangent matrix K, from which scattering phase shifts can be obtained, is defined by

$$K\left(\sqrt{s}\right) \;=\; -\left[1-k^{-1}M\;JXN\right]^{-1}\;\left[k^{-1}M\;JXJ\right]\quad . \tag{3}$$

In this equation, the diagonal matrices J and N contain the two linearly independent Bessel and Neumann scattering solutions above threshold, respectively, or their analytic continuations below threshold, for each of the two-meson channels. The diagonal elements of the reduced-mass matrix M are calculated by using the relativistic formula

$$4s^{3/2}M_i\left(\sqrt{s}\right)=\left[s^2-\left(m_{1i}+m_{2i}\right)^2\left(m_{1i}-m_{2i}\right)^2\right]. \tag{4}$$

The 28×28 matrix X introduced in Eq. (3) is defined as

$$X\left(\sqrt{s}\right) \;=\; 4\lambda^2\;V^TAV\quad , \tag{5}$$

where λ is the overall coupling constant related to quark-pair creation, and the 2×28 matrix V contains the relative coupling constants given in Table 1. The diagonal 2×2 matrix A contains products of the two linearly independent solutions of the harmonic oscillator. It is this matrix for which an RSE expansion can be formulated.

Except for the matrix V, all matrices are diagonal, because we do not consider direct interactions in either of the two sectors. More details can be found in Ref. [17].

From Ref. [17], we adopt here the effective constituent quark masses $m_c=1.562$ GeV and $m_s=0.508$ GeV, and the oscillator frequency $\omega=0.19$ GeV. However, we cannot use the scaled dimensionless radius ρ_0 from Ref. [17], since it corresponds to the maxima of different transition potentials [15], not their effective radii. In Ref. [13] we used 5 GeV^{-1} for $K\pi$ in a P wave, which gives $\rho_0\approx1$, and 3.2 GeV^{-1} for $K\pi$ in an S wave, yielding $\rho_0=0.66$. For simplicity, we choose here $\rho_0=0.8$, as a kind of average value for the different waves under consideration (see Table 1), corresponding to a distance of 0.58 fm. The overall coupling λ we vary such that the ground state of the spectrum, i.e., the $D_s^*(2112)$, gets its experimental [18] mass.

3 OZI-forbidden decays

Our initial findings, with OZI-allowed channels only, are the following. We obtain a narrow resonance at about 2.6 GeV. Its width and position depend on the invariant radius ρ_0. For the above value of $\rho_0 = 0.8$, the resonance comes out at 2.613 GeV, and has a width of 6.5 MeV. Hence, contrary to what might be expected from naive perturbative calculations, we obtain a *narrow* resonance for a system having more than enough phase space for OZI-allowed decay. The reason appears to be twofold. First of all, most of the probability of $^3P_0$ pair creation goes into closed channels, which only give rise to a real mass shift. Secondly, the first radial excitation we are assuming for the $D_{sJ}^+(2632)$, albeit mixed with the 1^3D_1 state, has one node (see also Ref. [11]), which cannot lie far away from the the delta-shell radius ρ_0, on the basis of general size arguments. In the more realistic picture of Ref. [17], where a smooth transition potential was used, the convolution of this potential with the sign-changing wave function of the "bare" $D_{sJ}^+(2632)$ will lead to a partial cancellation. So the total width due to OZI-allowed decays could be considerably smaller than what is generally assumed.

Now, once we have a full solution of the coupled-channel problem, i.e., the complete S matrix, we may determine branching ratios for other types of decay modes, namely OZI-forbidden processes. However, one of these happens to contribute to the very $D_s^+\eta$ mode, already included in the list of OZI-allowed decay channels. Notice that an OZI decay to $D_s^+\eta$ can only proceed via $s\bar{s}$ pair creation, whereas the non-OZI decay may take place through both $u\bar{u}/d\bar{d}$ and $s\bar{s}$ creation. Precise values for such OZI-forbidden decays have to be estimated, since we do not dispose of a lot of experimental data on such processes when alternative OZI-allowed modes exist, too. Here, we estimate that up to 4–5 percent of the total probability of strong decay contributes to OZI-forbidden decays, which we account for in an effective way by correspondingly increasing the coupling constant of the OZI-allowed $D_s^+\eta$ channel. Note that this estimate of 4–5% seems quite reasonable on the basis of experimentally known [18] OZI-forbidden two-particle decays of mesons, keeping also in mind that the mentioned suppression due to the nodal structure of the wave function may not apply to non-OZI decays. In Table 2, we present the results, after refitting the overall coupling constant to the $D_s^*(2112)$ mass, for the effect of the non-OZI $D_s^+\eta$ decay mode on the $D_s^{*'} \to D^0K^+ \,/\, D_s^{*'} \to D_s\eta$ branching ratio, as well as the total width. We see that the surprising branching ratio $D_s^{*'} \to D_s\eta \,/\, D_s^{*'} \to D^0K^+ \approx 6$ observed by the SELEX collaboration [1] is reproduced for a non-OZI contamination of about 4.3%, implying a total width of some 8 MeV, which is also compatible with the data. Of course, the latter experimental findings need further confirmation. What our results show is that such a scenario is plausible.

non-OZI (%)	peak (GeV)	$\frac{D_s^{*'} \to D^0 K^+}{D_s^{*'} \to D_s \eta}$	Γ (MeV)	λ
0	2.613	10.46	6.5	2.67
0.31	2.613	4.47	6.6	2.66
0.62	2.613	2.52	6.6	2.65
0.93	2.612	1.69	6.9	2.63
1.23	2.612	1.18	7.0	2.62
1.85	2.611	0.67	7.2	2.60
2.47	2.611	0.43	7.4	2.58
4.32	2.610	0.17	7.9	2.51

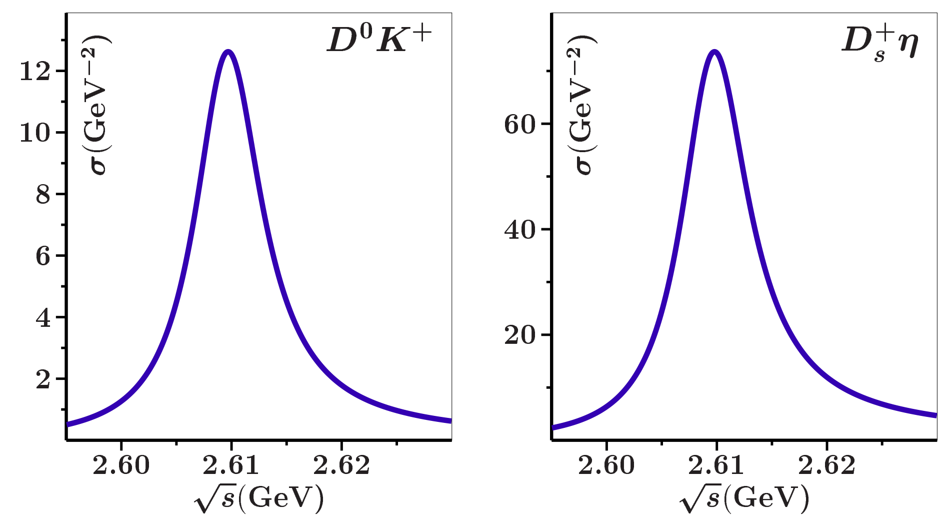
Table 2: The $D_s^{*'}$ central resonance position, the branching ratio of $D_s^{*'} \to D^0 K^+$ to $D_s^{*'} \to D_s \eta$, the total width of the $D_s^{*'}$, and the effective overall coupling constant, as a function of the percentage of non-OZI w.r.t. OZI hadronic decay modes.

4 P-wave cross sections for $c\bar{s}$ decay.

In this section, we present some figures for the computed partial cross sections, corresponding to the case which reproduces the SELEX decay-rate ratio (4.32% in Table 2).

4.1 The $D_s^{*\prime}$ resonance.

In Fig. 1, we depict the theoretical cross sections for D^0K^+ and $D_s^+\eta$ in the total-invariant-mass ($\sqrt{s}$) region of 2.6 GeV. We observe a resonance with a central mass about 20 MeV below the SELEX value, and a width of 7.9 MeV. Moreover, we see



(a) (b)

Figure 1: Theoretical cross section σ for D^0K^+ (a) and $D_s\eta$ (b) P-wave scattering, from a multi-coupled-channel calculation (model parameters taken from Ref. [17], except for the transition-potential parameters).

that about 6 times more $D_s^+\eta$ pairs are produced than D^0K^+ pairs. This resonance has here vector-meson quantum numbers, i.e., $J^P = 1^-$.

4.2 Further P-wave D^0K^+ cross sections.

In Figs. 2 and 3 we show other structures we find in D^0K^+ P-wave scattering, in the mass region from threshold up to 3.1 GeV.

Close to the D^0K^+ threshold and well below the $D_s^+\eta$ threshold, we find a structure with a width of some 100 MeV (see Fig. 2). Notice, however, that the peak cross section is only 0.005 GeV^{-2}. Whether such a weak signal can be observed in experiment looks doubtful. This threshold effect is clearly due to the bound-state pole of the $D_s^*(2112)$, and does not correspond to a resonance, since we do not encounter any additinal pole in this energy region.

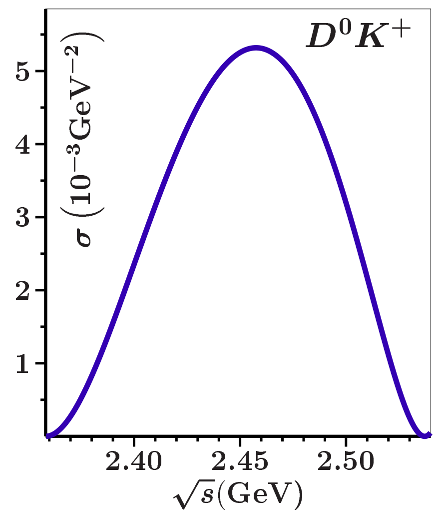


Figure 2: A broad but tiny theoretical signal in D^0K^+ P-wave scattering below the $D_s\eta$ threshold.

For energies higher than the $D_s^{*\prime}$ mass, we find three signals (see Fig. 3): two narrow resonances at 2.72 GeV and 3.08 GeV, and one broad signal at 3.03 GeV. OZI-forbidden decay modes may very well broaden the two narrow structures. So

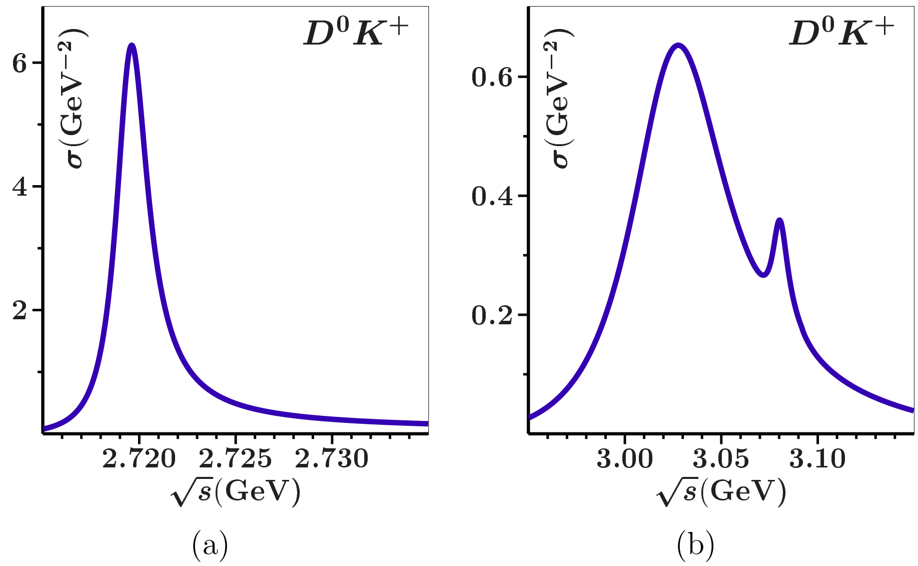


Figure 3: Details of the predicted resonances with central masses at 2.72 GeV (a); 3.03 and 3.08 GeV (b). Their widths are about 2, 60, and 8 MeV, respectively.

what exactly can be found in experiment, is not entirely clear from our predictions. We only assure that narrow companions to the $D_{sJ}^{+}(2632)$ should exist. Their positions are predicted here within the model error of some 50 MeV. The broader resonance at 3.03 GeV, with a width of 50–60 MeV, should be reasonably easy to observe experimentally.

5 Conclusions

The experimental confirmation of at least some of the here predicted signals will contribute strongly to our understanding of the $c\bar{s}$ spectrum.

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References

[1] A. V. Evdokimov [SELEX Collaboration], arXiv:hep-ex/0406045.

[2] R. Brandelik *et al.* [DASP Collaboration], Phys. Lett. B **80**, 412 (1979); **70**, 132 (1977) (DESY reports 78/63 and 77/44, respectively).

[3] Stephen Godfrey and Nathan Isgur, Phys. Rev. D **32**, 189 (1985).

[4] D. D. Brayshaw, Phys. Rev. D **36**, 1465 (1987).

[5] T. Barnes, F. E. Close, J. J. Dudek, S. Godfrey, and E. S. Swanson, arXiv:hep-ph/0407120.

[6] S. Okubo, Phys. Lett. **5**, 165 (1963); G. Zweig, CERN Reports TH-401 and TH-412; see also *Developments in the Quark Theory of Hadrons*, Vol. 1, pp. 22–101 (1981), edited by D. B. Lichtenberg and S. P. Rosen; J. Iizuka, K. Okada, and O. Shito, Prog. Theor. Phys. **35**, 1061 (1966).

[7] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, arXiv:hep-ph/0407025.

[8] Y. R. Liu, Y. B. Dai, C. Liu, and S. L. Zhu, arXiv:hep-ph/0407157.

[9] Y. Q. Chen and X. Q. Li, arXiv:hep-ph/0407062.

[10] B. Nicolescu and J. P. B. de Melo, arXiv:hep-ph/0407088.

[11] K. T. Chao, arXiv:hep-ph/0407091.

[12] E. van Beveren, G. Rupp, N. Petropoulos, and F. Kleefeld, AIP Conf. Proc. **660**, 353–366 (2003) [arXiv:hep-ph/0211411].

[13] E. van Beveren and G. Rupp, Eur. Phys. J. C **22**, 493 (2001) [arXiv:hep-ex/0106077].

[14] E. van Beveren and G. Rupp, Phys. Rev. Lett. **91**, 012003 (2003) [arXiv:hep-ph/0305035].

[15] E. van Beveren, Z. Phys. C **17**, 135 (1983); **21**, 291 (1984); E. van Beveren and G. Rupp, Eur. Phys. J. C **11**, 717 (1999) [arXiv:hep-ph/9806248].

[16] E. van Beveren, C. Dullemond, and G. Rupp, Phys. Rev. D **21**, 772 (1980) [Erratum-ibid. D **22**, 787 (1980)].

[17] E. van Beveren, G. Rupp, T. A. Rijken, and C. Dullemond, Phys. Rev. D **27**, 1527 (1983).

[18] S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592**, 1 (2004).

[19] K. Abe *et al.* [Belle Collaboration], Phys. Rev. D **69**, 112002 (2004) [arXiv:hep-ex/0307021].